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A Proposed Magnetically Enhanced Reactive Ion Etcher for ULSI

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***Abstract*—A new ultraclean (UC) Magnetically Enhanced Reactive Ion Etcher (MERIE) is proposed to overcome the limitations of the present-state MERIE available commercially. The sensitivity of gas compositions, pumping speed, substrate temperature and magnetic field intensity are discussed as the examples of hardware relating process limitations. Five major configuration changes are proposed in the system: 1) improved effective pumping speed; 2) supplementary magnets for uniform and stable plasma distribution; 3) dual RF excitation for independent control of ion energy and flux; 4) dc-biased shield electrode for minimum chamber material contamination; 5) dc-biased substrate. In dual excitation magnetically enhanced plasma equipment, the cathode self-bias becomes a logarithmic function of the excitation frequency. A logarithmic relationship is derived assuming a Maxwell–Boltzmann distribution. Also, the study with a dual RF excitation system found that dc-biasing the Si substrate in low energy SiO_2 etching process can significantly reduce Si etching rate by impeding positive ions from reaching the substrate. Of significance is that SiO_2 to Si etching rate selectivity can be significantly improved during the overetch step in SiO_2 etching of high aspect ratio contact holes. This is favorable in manufacturing of future ULSI devices because we no longer have to rely exclusively on the protective polymer formation.**

I. Introduction

PLASMA ETCHING, the reactive ion etching in particular, plays an important role in the fabrication of ULSI semiconductor devices. The rapid increase in device integration not only reduces the chip dimensions but also increases the number of process steps, requiring each process to be a high throughput process. The high rate and continuous enlargement of wafer diameter have driven equipment manufacturers in the semiconductor industry to focus their efforts on the single wafer architecture over batch systems in the late 1980s. More recent efforts focus on the implementation of "closed architecture" concept, which utilizes the multi-chamber configuration to achieve integrated processing required for advanced device manufacturing [1], [2]. Hence, the parallel development in both the advanced equipment and devices are inevitable.

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The conceptualization of plasma processing equipment, namely Magnetically Enhanced RIE (MERIE), involves deep understanding of vacuum science, plasma physics, chemical kinetics, gas dynamics, electrical networks, material science, etc. Contrary to the common beliefs, the concept of ultraclean (UC) technology [3] is also important in RIE and needs to be fully considered during the initial developmental stage. As the devices become highly sophisticated, uniformity, contamination and radiation damage issues have become extremely important. Under the UC concept, the process must be free of damage and contamination, and the highly repeatable process is achieved when the process variations are completely eliminated. Ohmi has demonstrated the importance of UC concepts in the sputter depositions of epitaxial aluminum, copper, and silicon films at the temperatures substantially lower than that of conventional methods [4]–[6].

In this paper, the fundamentals of MERIE are briefly reviewed, followed by examples of hardware-related process limitations of the commercially available MERIE [7], [8], e.g. the effects of pumping speed, temperature, process gas compositions and magnetic field, are discussed. Then, the newly designed ultraclean (UC) MERIE is proposed by utilizing the concept of dual RF excitation plasma processing equipment [9], [10]. In the dual RF excitation processing, the independent control of ion bombardment energy and ion flux can be achieved through applications of two separate RF electric fields to each electrode. Finally, the importance of the excitation frequency and dc-biasing of the shield electrode and substrate are discussed.

II. Magnetically Enhanced Reactive Ion Etching (MERIE)

In low pressure plasmas, since the mobility of electrons is strongly impeded by the presence of a magnetic field perpendicular to the electric field, the ionization efficiency of the magnetically enhanced plasma becomes significantly higher than the conventional RIE plasma [11].

Rate Controlling Kinetics

Conventionally the plasma equipments including plasma etching systems have been developed with minimum consideration of the hardware related process limitations. In order to meet the rapidly advancing process requirements, the fundamentals of the etching process which can be significantly influenced by the hardware configurations of the current plasma processing equipment need to be clarified. In this section, the etch kinetics is briefly reviewed. The basic kinetics model used by Coburn and Winters [12]–[15] in the conventional RIE can be directly applied to the MERIE processing.

The simplified kinetics model consists of five steps: 1) diffusion of reactants from the bulk flow to the substrate surface; 2) absorption of reactants on the surface; 3) surface reaction; 4) desorption of products into the following gas. The corresponding rate equations are as follows:

1) Diffusion of reactants

$$r_i = k_{mi}(p_i - p_{is}) \tag{1}$$

where

k_{mi} ~ mass transfer coefficient
p_i ~ partial pressure of bulk flow
p_{is} ~ partial pressure adjacent to the substrate surface.

2) Absorption of reactants

$$r_i = k_{ai} \cdot p_{is} \cdot C_0 - k_{di} \cdot p_i \tag{2}$$

where

k_{ai} and k_{di} ~ rate constants for absorption and desorption
C_0 ~ concentration of vacant active site
p_s ~ partial pressure on surface.

3) Surface reaction

$$r_i = r_i(p_s). \tag{3}$$

4) Desorption of products

$$r_i = K_{di} \cdot p_s - K_{ai} \cdot p_{is} \cdot C_0. \tag{4}$$

5) Diffusion of products

$$r_i = K_{mi}(p_{is} - p_i). \tag{5}$$

Although detail analysis of the etching mechanism in the magnetron plasmas is well beyond the scope of this study, the implications of above rate equations are extremely important in establishing the experimental matrix for the process optimization. For instance, the vapor pressure of the products on the surface must be significantly higher than the bulk partial pressure to facilitate the sufficient transfer of products. Any one of these sequential rate equations may become the "rate controlling" step, where the rate constants for that step is smaller than those for the other steps.

In RIE or ion assisted etching, high anisotropy is achieved by utilizing the bombarding energy of the positively charged ions to selectively activate the unprotected surface [16], [17]. The lateral etching caused by the presence of active species strongly hinders the high aspect ratio etching of submicron patterns.

III. Available MERIE Systems

Two magnetron plasma systems were employed in this study. a) The schematic diagram of the first system, the commercially available Applied Material PE-5000 is shown in Fig. 1. The system uses the four electromagnetic coils to rotate the magnetic field at 0.5 Hz. A variable magnetic field of 160 gauss at maximum was attained. The water cooled capacitively coupled cathode is powered by a 750 W, 13.56 MHz RF generator. The wafer was clamped to the cathode and helium was introduced to improve the thermal conductivity between the wafer and the cathode. The cylindrical aluminum chamber wall of approximately 13-inch in diameter served as an anode. The standard etching conditions used in thermal-oxide etching are: 30 mTorr, 600 W, 160 gauss, 6 Torr helium pressure.

A. Pumping Speed

Fig. 2 shows the effect of CO_2 addition to the oxygen chemistry used in the multilayer resist (MLR) lithography technique. By mixing CO_2 and O_2, the partial pressure of the etching gas (O_2) was reduced and simultaneously the partial pressure of the etched product (CO_2) was increased. Hence, the driving force $|p_i - p_{is}|$ for the diffusion of reactants to and of product from the etched surface with negligible external diffusion was lowered. When CO_2 concentration was gradually increased the lateral etching diminished and highly vertical profile was obtained at 1 : 1 mixture of O_2 and CO_2. In Fig. 3, the photoresist etching rate dependency on CO_2 concentration in O_2 plasma is shown. The etching rate gradually decreases with an increase in CO_2 concentration.

In order to achieve the uniform and highly repeatable etching results, the process conditions including chemical compositions and ion flux and energy over a large diameter wafer must be uniform. For example, the product gas accumulation in the bulk gas can significantly influence the process results in batch type systems. Even in single wafer etching systems, the effects become visible when the reactant gas flow is unidirectional over a large diameter wafer. Etching of an 8-inch Si wafer using a halogenated gas at a rate of 1 μm/min produces 2.61×10^{-3} g-mole/min of silicon byproducts in the gas phase. At the standard pressure (1 atm) and temperature (0°C), it is equivalent to 58.5 sccm of the product gas mixed with the reactant gas in the system. Consequently, the bulk compositions near the outlet becomes drastically different from the inlet compositions. Since a single wafer system must be able to etch at a rate perhaps 10 times faster than the conventional batch systems, considering added time required for pump down and vent cycles and economical reasons, both the volumetric rate of process gases supplied and the pumping capacity of the system must be comparable in size with the batch systems to minimize the variations in the process gas compositions over the substrate. Also, the flow pattern on the wafer surface should

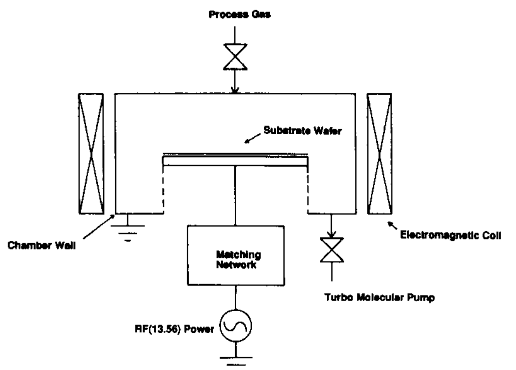

Fig. 1. Schematic diagram of PE-5000 magnetically enhanced Reactive Ion Etcher (MERIE).

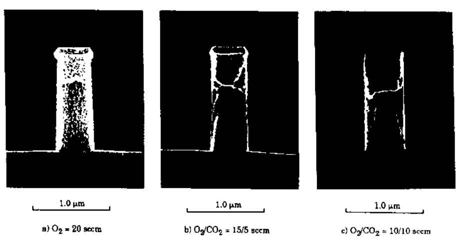

Fig. 2. Effect of CO_2 addition on profile control in MLR etching using O_2. Gas mixtures of a) 100% O_2, b) 75% O_2 and c) 50% O_2 were used. Pressure was 5 mTorr. RF power was 300 W. B-field was 40 G. Data obtained in PE-5000.

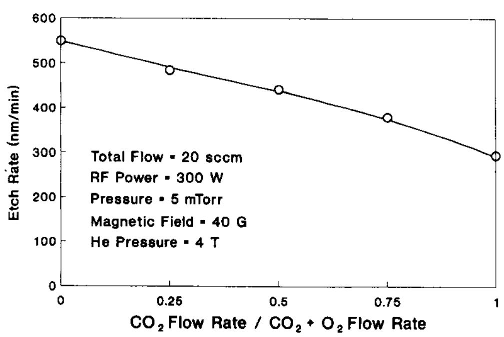

Fig. 3. Photoresist etching rate dependency on CO_2 concentration in O_2 based plasma. Data obtained in PE-5000.

be carefully considered to minimize the effect of the etch product accumulation. Typically, the single wafer RIEs are equipped with turbo-molecular pumps (TMP) of < 300 1/sec so that the maximum pumping capacity in the low pressure (10^{-3} Torr) regime will be substantially limited. For instance during the SiO_2 etching using CHF_3 based gases, the total flow rate was limited to < 70 sccm for the operating pressure of 30 mTorr. Our recommendation to alleviate the flow rate limitation is to utilize the tandem type magnetically coupled TMP [18]. The oil free TMP effectively eliminates the possibility of organic material contamination from lubricating oil and also enhances the flexibility in configuring the vacuum system.

B. Substrate Temperature

The wafer surface temperature determined by the energy balance equation significantly modifies the reaction rate constants. Due to the low heat capacitance of low pressure process gases, the heat transfer effects of the bulk gas flow becomes insignificant. The internal heat consumption or production due to etching reaction are also negligibly small in comparison with the RF power dissipated at the wafer surface [19]. Thus, the energy balance equation can be expressed simply as the radiation energy due to bombarding ions and electrons (Q_{in}) minus conduction loss through the wafer into the cathode ($D_0 \cdot \delta_T/\delta_Z$) equals the heat accumulation on the wafer surface ($C_p \cdot \delta_T/\delta_t$), where D_0 is the overall thermal conductivity.

Fig. 4 shows the effect of the backside helium pressure on Si and SiO_2 etch rates. The SiO_2 etch rate remained relatively constant while the Si rate gradually decreased resulting in a gradual increase in SiO_2 to Si selectivity.

Yin [20] *et al.* reported over 50% increase in the SiO_2 to Si selectivity by reducing the electrode temperature 30°C. Tachi [21] obtained an excellent side-wall control at the substrate temperature range of −110°C when Si was etched with SF_6 gas. Thus, the low temperature substrate is suitable for achieving anisotropic etching without a thick side-wall protection, i.e. undesirable for an accurate transfer of sub-half micron patterns. However, in production units the use of temperature range below −65°C, which is the minimum temperature range of multi-stage chillers, becomes impractical because of non-availability of rapid freezing and heating techniques.

C. Polymer Formation in Magnetron Discharge

In etching of SiO_2 in fluorocarbon plasmas, polymer formation further complicates the process [20], [22], [23]. In this process there are two competing reactions: etching and polymerization. The protective polymer formed on Si surface effectively protects the surface from being etched, so that highly selective SiO_2 etching is achieved. Since the bonding energy (8.28 eV) of Si-O is greater than Si-Si (3.39 eV) [24], conventionally the high selectivity process is generally obtained under the high energy sputter etching mode resulting the formation of an unfavorable damaged and carbon contaminated substrate layer during the over etched steps [25]–[28].

Figs. 5 and 6 shows the effects of CH_2F_2 addition to CHF_3 and C_2F_6 plasmas. The etch rates and selectivity for CH_2F_2 and CHF_3 mixture showed that the increase in the fluorine-to-carbon (F:C) ratio enhances the polymer formation and the wafer surface became completely cov-

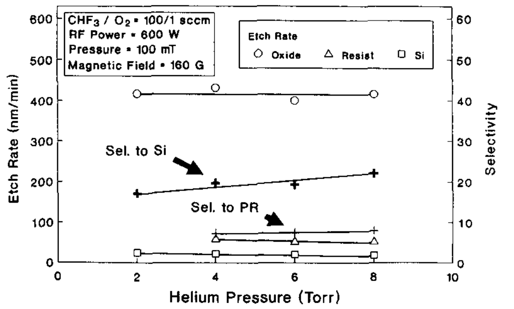

Fig. 4. Effects of the backside helium pressure on Si and SiO_2 etching rates. Resist masked SiO_2 was etched in CHF_3/O_2 (100/1 sccm) discharge. Pressure was 100 mTorr. RF power was 600 W. B-field was 160 G. Data obtained in PE-5000.

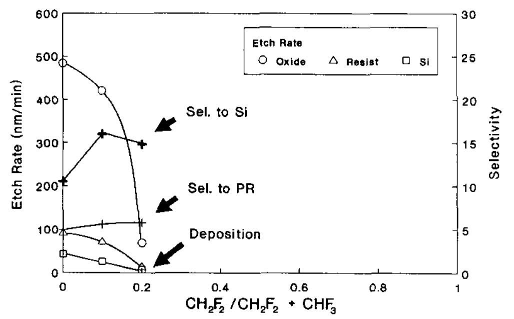

Fig. 5. Effects of CH_2F_2 addition in CHF_3 plasma on Si and SiO_2 etching rates. Etched conditions were: RF power = 600 W; pressure = 30 mTorr; B-field = 160 G; He pressure = 6 Torr. Total process gas flow rate was 62 sccm. Data obtained in PE-5000.

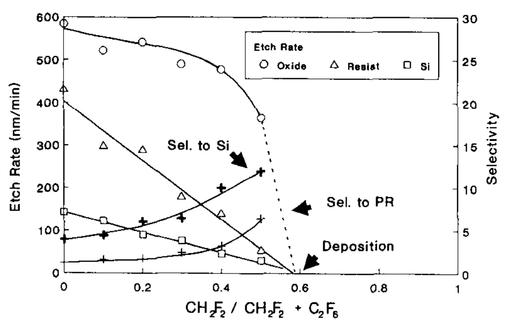

Fig. 6. Effects of CH_2F_2 addition in C_2F_6 plasma on Si and SiO_2 etching rates. Etched conditions were: RF power = 600 W; Pressure = 30 mTorr; B-field = 160 G; He pressure = 6 Torr. total process gas flow rate was 62 sccm. Data obtained in PE-5000.

ered with the polymer at CH_2F_2 concentration of 20%. The critical CH_2F_2 concentration for etch/deposition was much higher for the CH_2F_2 and C_2F_6 mixture. Although the F:C ratios were identical, the additional hydrogen dissociates from CHF_3 reduced the effective F radical concentration in the plasma by forming HF [23], [29].

Nevertheless, the highly selective process can be obtained near the critical concentration, where the process margin is extremely narrow and undesirable. Hence, the process-variation free process can be achieved when the wafer surface temperature and the gas compositions are accurately and uniformly controlled over the entire wafer surface.

D. Magnetic Field Effects

Since the bombarding energy of ions is primarily determined by the substrate self-bias, the radiation damage caused by high energy positive ions can be significantly reduced in the magnetron plasmas [30], [31]. In CHF_3/O_2 plasma, the self-bias dependence on the magnetic field intensity showed that the presence of the moderate B-field (110 G) reduced the substrate self-bias to almost one-fifth of the value measured without B-field. The self-bias reached less than -50 V when the B-field was increased to the maximum (160 G).

In another experiment, the silicon wafers subject to low energy Ar ion (10–60 eV) bombardment were evaluated for the oxidation induced stacking fault (OSF), subsequent to a steam exudation at 1050°C for two hours and Wright etching. The results showed weak trends in etch pit counts but no OSF was observed confirming the report by Watanabe [30].

The effect of varying the magnetic field intensity on Si and SiO_2 etch rates are shown in Fig. 7. The Si and SiO_2 rates increased with the increase in B-field reducing the SiO_2 to Si selectivity. One of the reasons for the gradual increase in Si etch rate is believed to be caused by the increase in the wafer surface temperature.

Fig. 8 shows the effect of magnetic field on the substrate temperature. The increased ionization and ion flux raised the wafer surface temperature, which was monitored by pasting the thermally sensitive tape on Si wafers. However, it should be noted that when the mean free path of electrons are long and wafer heating due to secondary electrons are significant, the magnetic field is very effective in reducing the wafer temperature as observed in the RF sputtering reported by Paradis [32].

Although the use of magnetron plasmas goes back a few decades, the concept of the rotational magnetic field used in PE-5000 is relatively new [33]. The advantage of the rotating magnetic field is that it eliminates the problem of the plasma shifting exist in the dc magnetron plasma. However, in a microscopic view, the system requires an additional improvement under the concept of the energy clean technology. This is associated with the instantaneous variation of the plasma density over the edge of large diameter wafers caused by the E $\times$ B drift of electrons. Savas and Donohoe [34] explain that the denser plasma in the east causes the sheath thickness to be less than the west. This causes increased capacitance per unit area for the sheath in the east which results in a lower impedance coupling between the electrode and the plasma. In other words, the plasma density becomes thinner in the west, which increases the RF impedance across the sheath.

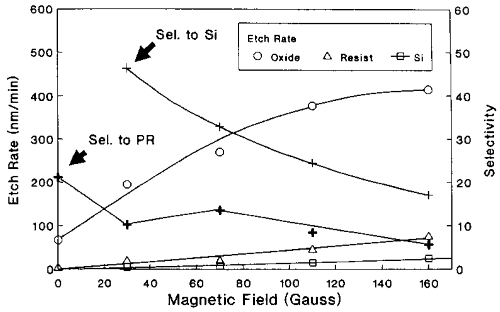

Fig. 7. Si and SiO_2 etching rates dependence on Magnetic field strength. Thermal oxide was etched in CHF_3/O_2 (100/1 sccm) plasma. Pressure was 100 mTorr, RF power was 600 W. He pressure was 6 Torr. Data obtained in PE-5000.

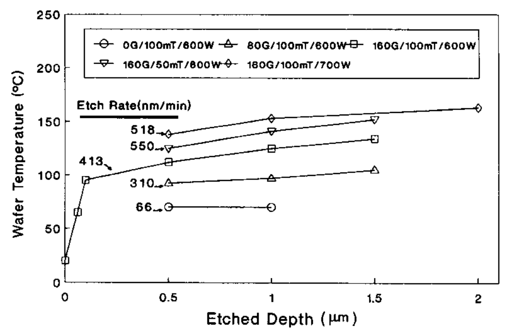

Fig. 8. Wafer surface temperature dependence on magnetic field strength. Temperature were normalized in terms of etched depth and corresponding etching rates are shown in the figure. Data obtained in PE-5000.

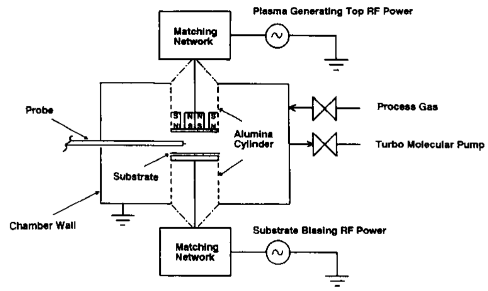

Fig. 9. Schematic diagram of dual excitation system used in this study.

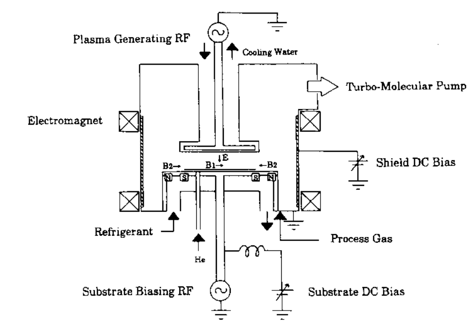

Fig. 10. Schematic diagram of UC magnetically enhanced reactive ion etcher.

For uniform RF field applied over the substrate, the RF amplitude becomes higher in the west, which causes the local self-bias to increase. Since the radiation damage depends on the maximum potential difference across the sheath, the transient variation in the dc potential of the substrate should be eliminated unless the changes are fast enough so that ions are only accelerated by the averaged value.

1) The schematic diagram of the second system is shown in Fig. 9. The system is a dual RF excitation system, having two separate variable frequency RF power units, capable of accurate control of the plasma density and the ion bombardment energy in the low energy regime (<50 eV). The static magnets were placed in the upper electrode for magnetic enhancement. The magnetic field intensity at the wafer surface is 50 gauss, where the etching rates were measured. The detail description of the advantages of the dual excitation plasma equipment (DEPE) have been reported elsewhere [10].

IV. Design of the UC Magnetically Enhanced RIE

The schematic diagram of the proposed system is shown in Fig. 10. In this system, additional pole-piece static magnets are placed surrounding the wafer. The cross section view of the electrode is shown in Fig. 11. When the $E \times B$ drift of electrons form a closed loop in the plasma, the high density plasma is formed without increasing the plasma potential [9]. Having the supplementary developed dense plasma in the outer perimeter of the wafer, the entire wafer surface will be constantly covered with a highly dense plasma. Also, in a dual excitation system, there will be a secondary $E \times B$ closed loop to further enhance the plasma uniformity. The uniformly distributed plasma should provide an uniform electrical conduction through the sheath and an uniform self-bias distribution over highly sensitive dielectric layers such as gate oxide to reduce electrical damage problem.

The framework of the hardware configuration is based on PE-5000 and DEPE. The proposed system is characterized by the five major modifications over PE-5000.

1) The protruded top electrode provides a large conductance through the top of the chamber for the maximum pumping speed permitting the vertical bottom to top flow pattern. The inverted flow pattern is selected to minimize the product gas accumulation effects and to improve the maintainability of the system. With a combination of 1000 liter/sec TMP and a dry pump, an operating pressure of 7×10^{-3} Torr with 250 sccm flow should be achieved.

2) The static magnets imbedded in the substrate electrode provides the supplementary source of the high density plasma minimizing the effects of the plasma sweep-

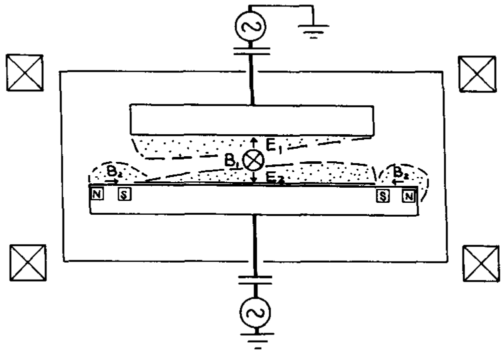

Fig. 11. Cross-sectional view of proposed system. E_1 & E_2 represent corresponding electrical fields present at top and bottom sheaths. B_1 and B_2 are magnetic fields of electromagnets and static magnets respectively.

System	RF Power Supplied	Magnetic Enhancement	Exhaust	Chamber Wall	Top Electrode Material	Substrate DC bias	Maximum Wafer Size
PE 5000	Single RF (13.56 MHz)	Electrically Rotating B-field	Axi-symmetrical Top-to-Bottom	Anodized Aluminum	Quartz	None	6"
Dual RF Excitation	Dual Excitation (High Plasma Generating Top RF Low Wafer Biasing RF)	Static B-field	Unidirectional Side-to-side with Maximum Conductance	Stainless Steel	Silicon	Present	4"
Proposed UC Etcher	Dual Excitation (same as above)	Electrically Rotating with supple-mentary Magnets	Axi-symmetrical Bottom-to-top with Maximum Conductance	DC Biased Aluminum with supple-mentary B-field	Silicon	Present	8"

Fig. 12. One to one comparisons of PE-5000, dual excitation system and proposed UC etcher.

ing. The electromagnets will be similar to ones used in PE-5000. However, in order to accommodate large diameter wafers, perhaps 10 inches in the near future, the inside diameter of each coil should be large enough for wafer handling.

3) The secondary high RF is applied to the top electrode for the plasma density control [10].

4)The cylindrical shield electrode attached to the chamber wall, completely RF-grounded by placing the extremely thin ceramics insulation between the shield and the chamber wall, provides the means for contamination control and the plasma potential reduction. Also, the RF-grounded shield biased by the DC power unit provides the self-cleaning capability [9].

5) The substrate DC-biasing is added for the ion current control and the etching rate control of the conductive substrate.

The process and the electrical considerations are fully implemented in the concept design of the proposed system. One to one comparisons of the proposed system with other two systems used in this study are shown in Fig. 12. The additional discussion on the shield electrode and the effects of substrate dc-biasing will be given in the next section.

V. Ultraclean Magnetically Enhanced RIE

A. Effects of Excitation Frequency

The sheath or voltage drop across the plasma and substrate serves two functions. When the reactive species are charged, they are efficiently transported across the dark space in addition to the diffusion driven mass transport. The kinetic energy of the charged particles are also transferred to the substrate surface raising the surface temperature. However, if the bombarding energy of ions exceeds the threshold sputter energy of the substrate, it can cause deterious effects on the etch results. In MLR etching process, for example, the high energy ions sputter the substrate aluminum creating nonvolatile oxidized aluminum complex on the side-walls of the bottom layer resist. Since the oxidized aluminum can not be removed in the following oxide mask removal step, an additional wet process is required. In another example, so called "rabbit ear" is caused by sputter deposition of silicon-based layer on sides of the resist mask which can not be removed by the subsequent O_2 ashing. In both cases, the deposited material results in the shifting of the patterned width. In all the above examples, the excessively high energy ions bombarding the substrate is the root cause of the problems, emphasizing the extreme importance of the accurate control of the ion striking energy in the low energy regime.

In Fig. 13, the effects of varying the excitation frequency on the self-bias voltage is shown for the Ar discharge. The result showed that the self-bias voltage, which became approximately one-half of the peak-to-peak RF voltage, is a logarithmic function of the excitation frequency for the constant power system. Hence, in the capacitively coupled dual excitation RIE, the application of the high frequency field (>100 MHz) delivered to the plasma generating electrode is suitable to minimize sputtering of the electrode material.

The logarithmic relationship can be derived based on the following assumptions:

1) simple capacitance approximation at sheath.
2) Maxwell-Boltzmann distribution.
3) constant sheath thickness at the cathode surface, i.e. the strong magnetic field (500 G) is sufficiently strong so that the sheath thickness becomes independent of the voltage drop across the electrode and the plasma.
4) density and temperature are invariant for the constant power discharge.

The RF current (I) across the cathode sheath of capacitance (Cs) depends on the excitation frequency (ω) and the applied voltage (V):

$$I = j \cdot \omega \cdot Cs \cdot V. \tag{6}$$

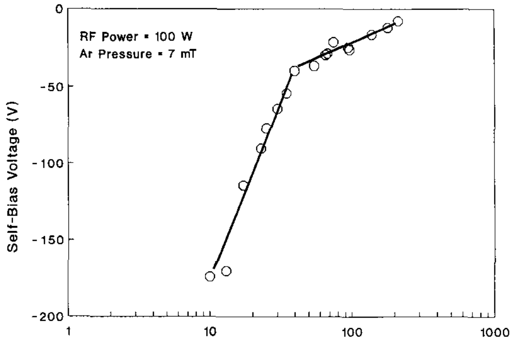

Fig. 13. Self-bias voltage dependence on excitation frequency in Ar discharge. Pressure was 7 mTorr. RF power was maintained at 100 W. Data obtained in dual excitation system.

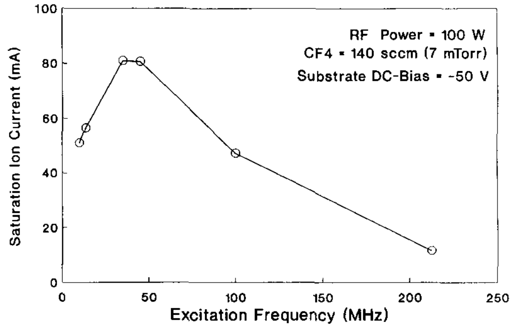

Fig. 14. Substrate ion saturation current for constant plasma generating RF power of 100 W in CF_4 plasma. Excitation frequency was varied from 10 ~ 212 MHz. Pressure was 7 mTorr. Data obtained in dual excitation system.

The application of Maxwell–Boltzmann distribution gives,

$$n(v) = n(0) \cdot e^{-(eV/\kappa Te)}. \tag{7}$$

In RF discharges, the electron conduction current is dominant over the displacement current and expressed as

$$I \propto e \cdot n \cdot \mu \cdot V. \tag{8}$$

For the constant pressure and magnetic field, the mobility remains the same and substituting (7) gives,

$$I \propto V \cdot n(0) \cdot e^{-(eV/\kappa Te)}. \tag{9}$$

Equating (6) and (9) and assumptions 3) and 4) give the following,

$$e^{-V} \propto \omega. \tag{10}$$

Let us consider the effect of the excitation frequency on the plasma impedance. The generalized equation for the RF current across the plasma is derived by Everhart and Brown [35]:

$$J(E) = \{(n_e e^2/m_e)/[v \cdot (1 + j\omega/v)] + j \cdot \omega \cdot \varepsilon_0\}. \tag{11}$$

Note that the equation contains only the density and frequency as variables. Equating the terms inside the parentheses gives the critical frequency at which the conduction current becomes equal to the displacement current.

$$\omega = \{n_e \cdot e^2/me \cdot \varepsilon_0\}^{0.5}$$

or

$$\omega = 898. \text{ MHz}. \tag{12}$$

Of course this is the "cutoff frequency" of electrons in our plasma. The review on the excitation frequency indicates that the conduction current is indeed dominant over the displacement current for radio frequency discharges.

The ion saturation current was measured in DEPE for the top electrode excited with RF of 10 ~ 212 MHz. The maximum saturation current was obtained at 40 MHz (Fig. 14). Since the ion DC current increases proportionally with the density of ions adjacent to the substrate, the maximum ion density is obtained when the plasma is generated with 40 MHz electric field. The plasma density dependence is believed to be caused by the presence of the residual inductance in the substrate RF path. The residual inductance becomes significant part of the network for the higher frequency and the plasma is no longer confined between the electrodes developing significantly less intensive plasma between the cathode and the chamber walls.

Knowing the residual inductance, the degree of RF coupling between the top electrode and the chamber wall can be estimated. Since the concept of DEPE is employed for the independent control of the plasma density and the ion bombardment energy, the application of DEPE in RIE requires that the plasma generating RF must be as high as possible to minimize the sputtering of the electrode material. In order to avoid the problem of standing wave, the maximum excitation frequency of 200 MHz is suggested. Then, the allowable residual inductance for that frequency becomes < 0.042 μH assuming the other parameters are held constant. Thus, the residual inductance of the substrate electrode must be reduced to a minimum so that the plasma generating RF can be effectively grounded at the substrate maximizing the intensity of plasma between the electrodes.

B. DC Biasing Effects of Supplementary Shield and Substrate

In the past, the dielectric materials such as quartz and anodized alumina have been applied as the covering materials of the chamber walls. However, since the ion bombardment energy in the low energy regime can be significantly affected by the plasma potential, the spatial distribution of the plasma should be rigorously controlled.

Fig. 15 illustrates the simplified electrical diagram of the equipment proposed in this paper. The effects of the dc-biased shield, the supplementary electrode, have been reported [9]. We found that the plasma potential as well as the chamber material contamination are significantly influenced by the shield dc potential. As shown in the fig-

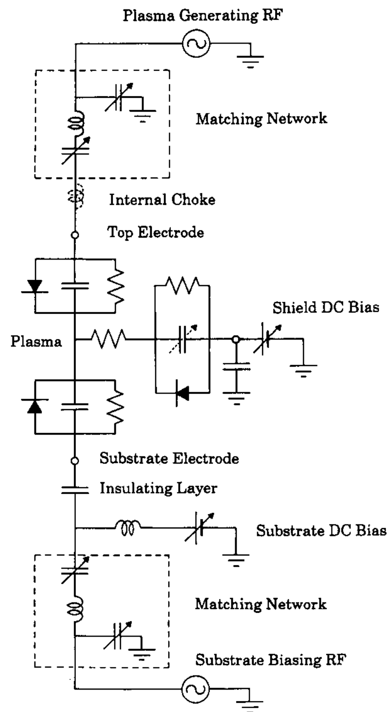

Fig. 15. Simplified electrical diagram of the dual excitation plasma equipment proposed in this study. DC biased shield effectively controls the plasma potential and minimizes sputtering of shield material. DC biased substrate improves SiO_2 to Si selectivity during the overetch step in etching dielectric films.

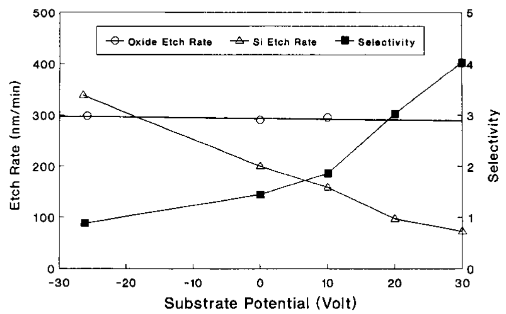

Fig. 16. Effects of substrate DC-biasing on Si etching rate and SiO_2 to Si selectivity. Plasma was developed with 100 MHz RF (100 W) applied from the top electrode. Substrate was RF-biased with 35 MHz RF (5.8 W). Pressure was 7 mTorr. CF_4 flow rate was 140 sccm. Data obtained in dual excitation system.

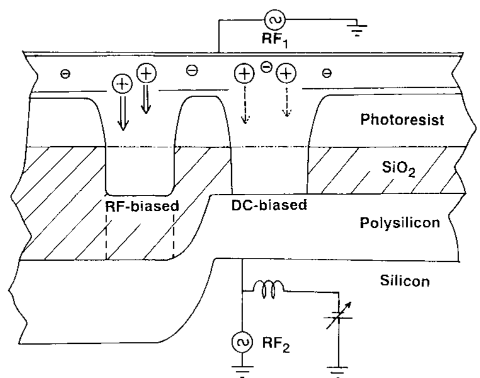

Fig. 17. Simplified drawing to illustrate the concept of dual excitation with substrate dc biasing.

ure, which is derived assuming the system to be a lumped element circuit for the frequency range we employed, varying the dc potential of the shield electrode effectively reduces the capacitance across the sheath developed between the shield and plasma. Hence, the plasma dominantly becomes resistively coupled with the shield allowing the direct control of the plasma potential.

In this study, the effect of dc-biasing the substrate was investigated in the dual RF excitation reactive ion etching of SiO_2. Si and SiO_2 wafers were etched in CF_4 plasma generated by 100 MHz (100 W) RF and the substrate was biased by 35 MHz. Fig. 16 shows the effect of dc-biasing the substrate. Since the SiO_2 surface potential was determined by the RF-biasing, the SiO_2 etch rate is not affected by the dc potential of the substrate. The Si etch rate, on the other hand, is substantially reduced at higher dc potentials.

The results indicate that SiO_2 to Si selectivity can be significantly improved by positively dc-biasing the conductive substrate. Since the unfavorable ion current to the Si substrate is reduced, the positively biased substrate is perhaps effective in reducing the wafer temperature. Note, however that at substrate bias of +30 V, which is approximately 10 V above the plasma potential, the resist mask started to reticulate indicating the rise in wafer temperature due to the excessive electron current. The concept of dual excitation RIE with dc biased substrate is illustrated in Fig. 17.

V. Conclusions

The fundamental kinetics and conservation equations were revisited to enhance our understandings on the magnetically enhanced etching, confirming the applicability of the traditional kinetics model. The hardware related process limitations of the commercially available MERIE were presented and countermeasures were proposed to alleviate such problems under the concept of UC technology. The five major modifications were suggested in the proposed UC MERIE over the currently available MERIE.

The self-bias voltage of the cathode became a logarithmic function of the excitation frequency and the relationship was verified assuming a Maxwell–Boltzmann distribution.

DC-biasing of the substrate in the dual RF excitation plasma was found to be an effective method of controlling the positive ion current to the substrate. Hence, the improved selectivity to the conductive substrate became possible without relying exclusively on the polymer formation mechanism.

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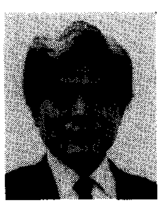

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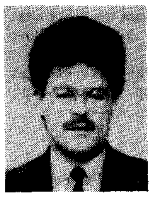

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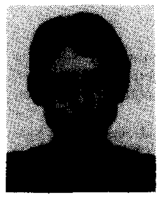

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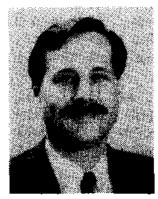

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